OUT-OF-PLANE ROTATIONAL HALF-GEAR ACTUATION IN MCNC MUMPS PROCESS

Duane Kubischta and Nathan Ota

Berkeley Manufacturing Institute 2111 Etcheverry Hall Berkeley CA 94720

ABSTRACT

This paper presents a design for obtaining a controlled rotational motion of a structure within a hinged plane orthogonal to the substrate using the MCNC MUMPS process. The maximum rotational freedom achieved by this design is 110 degrees with an accuracy of one degree. The motion is generated by a dual inchworm comb drive in which protruding driver pegs toggle the circular gear teeth. This successful model is the first attempt at progress towards unlimited 360 degree controlled rotation in an orthogonal plane.

INTRODUCTION

As more MEMS based applications are developed, a need arises for controlled motion within an orthogonal plane. These sort of design will require more complex MEMS structures, but complexity is constrained by the number of structural layers of polysilicon.

Many types of structures and actuators in MUMPS have already been developed and are continually being refined. These include: gears, hinged plates, locking hinged plates, electrostatically driven linear actuators, electrostatically driven inch worm drives and gears, and planar thermal actuators. What has not yet been designed is gears that operate about an axis orthogonal to the ground plane.

This paper presents one feasible out-of-plane rotational actuation assembly. Figure 1 presents a diagram of this type of motion. Here, a gear and hinge are fabricated on a plane which is propped up. This assembly can be accomplished manually with a probe. Additional assembly methods, such as self assembly, are increasingly popular but are not addressed in the scope of this paper. Furthermore, the plane must rotate about hinges and be locked into place. The motion generation is assumed to be in-plane to take advantage of existing designs. The final element is the motion transduction which converts in-plane motion to out-of-plane motion.

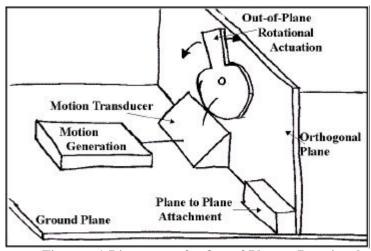


Figure 1:Diagram of Out-of-Plane Rotational Actuation

For the given schematic set-up shown in Figure 1, a variety of design choices are available for each element. Each choice presents its own set of tolerances and constraints. Additionally, the fabrication process has its own set of factors.

DESIGN OF TEST STRUCTURES

The principle design process in this paper is MCNC MUMPS. This process consists of two layers of structural polysilicon. The details and design rules for this process are found in the reference by D. A. Koester. The MUMPS process was specifically chosen in order to obtain a functional device within a short time frame and at a low cost. This well characterized fabrication process also has lots of proven designs for elements of our set-up, such as electrostatic drives and hinges.

The two structural layers of polysilicon limit the rotational gear design to a hinged plate half gear. The concept of a hinged plate half gear is presented in Figure 2. By carefully controlling the location of connectors between layers it is possible to have a contained rotational structure within only two poly layers. The draw back of this design is that the entire rotation is limited by the gear teeth engagement to a maximum of 120 degrees. Figure 2 shows the concept with a rotation of 90 degrees.

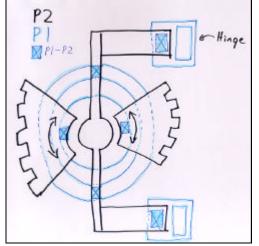


Figure 2: Diagram of Half-Gear Concept.

The choice of hinge mechanism effects the tolerance of the final location of the gear teeth. In this design, a combination of several different hinge designs is realized. Pister presents a simple MUMPS staple hinge [7] and Friedberger proposes a more accurate hinge mechanism using a modified two-poly process. [4] We use an alternating cantilever hinge design with minimum MUMPS spacing shown in Figure 3. By using a side step on the rotated plane, this allows a vertical tolerance of less than 0.75 microns. A maximum horizontal tolerance is determined by the MUMPS design rules at $\pm 3.0 \,\mu\text{m}$. (This is actually much lower due to the conformal ox2 layer, but is still given as a maximum. Friedberger showed accuracy to $\pm 0.75 \mu m$.) The different positional tolerances are shown in Figure 4. The lateral displacement can be minimized through the use of side locking hinged plates.

The MUMPS design rules also determine the positional tolerance of the gear within the hinged plate. Figure 4 also illustrates these tolerances. The design spacing determines the vertical misalignment while the sac2 thickness sets the horizontal motion. Additionally, the gear may torque within the plate to a maximum amount given in formula 1.

- (1) $x = R_{\text{teeth}} * \alpha$, where α is given by (2)
- (2) $\alpha = (Maximum diameter of spacing)^*(Layer spacing)$

The sum of all these tolerances determines the spacing of the driver mechanism.

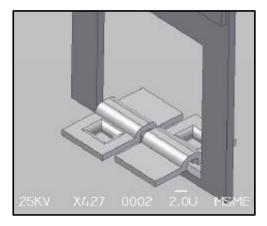


Figure 3: Alternating Cantilever Hinges

Type of Tolerance	Amount	Source	Diagram
Horizontal Plane	+3um, -3um	Hinge	
Vertical Plane	+0.75um	Hinge	
Lateral Plane	>lum	Ignored	
Horizontal Gear	-0.75um	Sae2 MUMPS	N
Vertical Gear	+2um, -2um	MUMPS seperation	
Torque Gear	x=R _{iesth} *alpha 0.5um	Sac2 MUMPS	Q

Figure 4: Positional Tolerances in hinged Gear

The next design challenge is to design a motion generator and transducer for an out of plane gear. Driving an out of plane gear presents a different set of requirements than planar gears. The main requirement is the driving point for an out of plane gear is limited to the point of tangency with the wafer plane. In addition, the positional tolerances for the out of plane gear are much larger than for a planar gear as discussed previously.

The first design option is a planar gear driven by inchworm motors. A planar gear would be created on the Poly2 layer, or possibly using Poly1 if Poly0 is utilized as a structural layer. Two inchworm motors, similar to those proposed by Yeh and Pister[8], would be on alternate sides of the gear. Rotation of the gear would be produced as the driver arms moved in an alternating fashion. The motion would be transferred to the out of plane gear as the two meshed. While this method of motion has been established, two major limitations eliminate this design. First, the variation in position of the components would include the gear-to-gear and arm-to-gear variations. Thus, the uncertainty of component location would be too large. More importantly though, the hinge that translates the out of plane

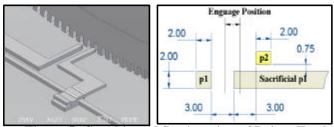


Figure 5: Graphic and Section-view of Driver Teeth

gear would need to perfectly mesh the two gears. Due to the large process tolerances in MUMPS, meshing two orthogonal gears seems to be quite difficult.

The third design option is a dual inchworm system similar to that of the first design. The design conceptually based on the gap closing actuator design by Yeh and Pister[8]. As seen in Figure 6, an outer inchworm motor surrounds an inner inchworm actuator. Each inchworm motor has one xdirection and one y-direction comb drive. Each motor has one tooth located at the front of the arm. In order to drive the out of plane gear, both motor teeth must engage the gear at the point of tangency. Therefore, the outer inchworm tooth is formed with Poly1. The inner inchworm tooth is formed with Poly2. A special raiser, or sacrificial Poly1 slab, is created to ensure clearance between the two teeth. The sacrificial raiser is designed to be discarded before operation of the gear. The teeth, when at rest, are designed to mate with the outside surface of the out of plane gear when it is locked into position. To, engage the tooth, the y-direction comb drive must be powered, causing the tooth to move forward to the engaged position. This design eliminates the difficult task of meshing the out of plane gear during translation out of plane. Moreover, once the gear is locked into position, the inchworm motors can be manually calibrated to the correct starting positioning before operation; thus, ensuring proper initial engagement.

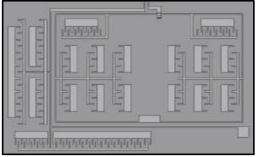


Figure 6: Dual Inch Worm Driver Mechanism

While gap closing actuators are a possible actuation method as Yeh and Pister[8] proposed, the required distances that the arms must travel make comb drive actuators more suitable. The gear design previously proposed would require four microns lateral motion to rotate the gear one degree. Moreover, the positional variability of the out of plane gear required a ten micron longitudinal translation to ensure tooth engagement. Therefore, the x-direction comb drive requires a minimal ten-micron spacing between teeth to allow for the longitudinal translation. Likewise, the y-direction comb drive fingers are spaced four microns apart.

Based on the dimensional requirements for the comb drive teeth, a rough estimate of the driver size can be formulated. The force provided by a comb drive is given by

$$F_z = 2N_f \left(\frac{\boldsymbol{e}_o V^2}{2}\right) \left(\frac{t}{z}\right)$$

The number of fingers in the comb drive is N. The finger depth and spacing are t and z respectively. Ignoring frictional forces and stiction in the gear, the electrostatic forces can be approximated as the force required to displace a simple cantilever or cantilever and simply supported beam combination. The force for a cantilever beam is given by

$$P = \frac{6dEI}{a^2(3L-a)}$$

The length of the cantilever is L, while location of a concentrated force that is applied. The displacement of the cantilever end is δ . The force required to displace a simply supported beam is given by

$$P = \frac{48 dEI}{L^3}$$

Optimizing the length of the beams so that the beam length equals the required length for the teeth, the latitudinal arms are roughly 350 microns and driven by 25 teeth. Likewise, the longitudinal arms are roughly 200 microns and driven by 15 teeth.

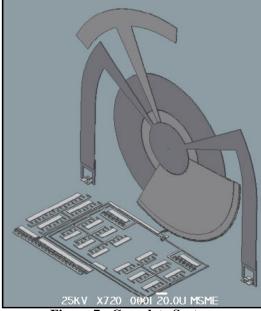


Figure 7: Complete System

EXPECTED RESULTS

We have presented a fully functional design for a hinged plate gear rotation. We expect that this design will actually work. If it does, the next step is to work towards quantifying the stiction on the gear as it rotates. This can be accomplished by measuring the voltage it takes to drive the gear.

APPLICATIONS AND FUTURE WORK

The presented work is designed to be a preliminary investigation on the feasibility of out-of-plane rotational motion. However, in making the particular design choices, certain sacrifices were made. In particular, a rotation of only 110 degrees was realized. This limitation is a direct effect of having only two structural layers. Several design options for achieving 360 degree rotation present themselves.

Within the MUMPS process, a single post-process timed etch of the poly0 layer can enable a third structural layer. A concentrated, timed HF etch removes the nitride layer and releases the Poly0. This concept was successfully demonstrated by J. Black and is illustrated in Figure 8. [Ref. J. Black] Additionally, the Sandia SUMMIT processes have multiple structural layers which could take advantage of concepts learned through the presented results.

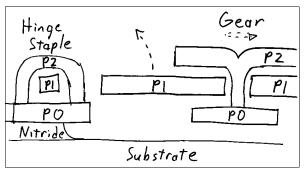


Figure 8: Poly0 as a structural layer in hinged gears.

CONCLUSION

In conclusion, the objective, to develop a mechanism to achieve out of plane motion using the MUMPS process, has been achieved. A two structural layer design essentially weaves two plates, thereby allowing a constrained method to hold a gear out of plane. One limitation of such a design is the limited rotational freedom. In addition, a dual inchworm motor is proposed to drive the gear. The drive design eliminates a previously difficult task: the need to mesh an out of plane gear with an in plane gear during rotation of the hinge. With further experimentation and refinement of the proposed system, out of plane rotation using the MUMPS process can become a standard functionality.

ACKNOWLEDGMENTS

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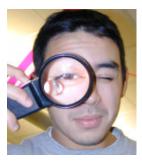
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Duane Kubischta was born on July 2, 1977 in San Diego CA. He received his B.S. in Mechanical Engineering from Berkeley in 1999 and is working towards a M.S. in Mechanical Engineering with an emphasis in design. He has also been a member of the state-champion California Ski Team for the past four years.

Nate Ota was born on May 5, 1979 in Jamestown, New York. He received his B.S. degree in mechanical engineering in 2001 from Carnegie Mellon University, Pittsburgh, PA. He is currently working on his Master's degree in mechanical engineering design at the University of California at Berkeley.